MANUAL CONTROL OF THE LANGLEY LABORATORY TELEROBOTIC MANIPULATOR

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ABSTRACT

LaRC has recently supported development of a new, precision, dual-arm telerobotic manipulator system which has seven degrees of freedom in each arm. As delivered to Langley, the mode of control implemented is master/slave from a pair of kinematically identical master arms with force reflection; however, robotic or manual control from a variety of different input devices can be implemented. Manual control of seven-degree-of-freedom, replica, force-reflecting master/slave manipulator arms has until recently been a matter of speculation since real systems have not been available for experimentation much less practical application. Langley's new Laboratory Teleoperator Manipulator (LTM) provides not only this capability but also in two arms simultaneously. This paper describes the LTM, its installation at LaRC and plans for a comparative evaluation study of various control input devices to the system. The control input devices comparison will include at least control from the system's basic master arms, six-degree-of-freedom hand controllers, Kraft minimasters, and the Jet Propulsion Laboratory (JPL) force reflecting hand controller. The initial master/slave control studies will consist of evaluating performance of simple task board operations as well as more realistic tasks typical of those a manipulator system might actually be required to perform in space.

INTRODUCTION

The Shuttle Remote Manipulator System (RMS), though crude, has demonstrated that telerobotic manipulator arms can perform useful tasks in space. It has launched satellites, repaired broken ones, acted as a mobile platform for astronauts building trusses in space, and dealt with many other unexpected problems. But jobs of much greater complexity, beyond the capability of the RMS, and often requiring the coordinated motion of more than one arm will be required in the near future. Very large orbiting stations will have to be built to gather solar power for retransmission, to accommodate a variety of other similar operations, and to accommodate a variety of other similar operations. It will not be practical, or perhaps even possible, to assemble these expansive orbiting platforms with simple telerobotic arms like the RMS or with EVA astronauts alone. NASA will need advanced automation, robotics, and telerobotics with a high degree of sensory feedback to make assembly of these space platforms a practical reality.

Basic research is ongoing at several NASA installations to create the enhanced telerobotic capabilities needed. Progress has been made, but most of the technology has been developed and evaluated at the part-task level. Development has centered around modified industrial manipulator arms such as the Unimate PUMA which are not designed for space operations or for the robotic generally needed in space applications. What has been needed is a systems level testbed based on new manipulators designed specifically to accommodate the operational constraints of space.

At Langley Research Center, we are assembling a new research laboratory which will begin to address this need. The focus of the new facility is a new manipulator system called the Laboratory Teleoperator Manipulator (LTM). It is a new, one of a kind, manipulator built by the Oak Ridge National Laboratory under the direction of the Langley Research Center to accommodate the tasks and conditions of space operations. The LTM is a full, dual-armed, force reflecting, master/slave manipulator in its basic form. It also has the full robotic capability in which both the slave arms function under total computer control. The master arms can be controlled similarly. The arms are designed to have a high degree of modularity. Most links can directly replace each other on the master and slave. Friction drives in the joints are used, rather than gears to minimize backlash and provide the more repeatable and effective positioning needed for robotic control. The LTM employs seven degrees of freedom (DOF) in each arm to give each of them one redundant degree of freedom for configuration control and singularity avoidance.

At Langley the LTM slave is being placed on a specially-built tracked carriage with a turntable which provides one translational degree of freedom as well as one additional rotational one.

The first studies to be carried out in the Teleoperator Systems Research Laboratory (TSRL) will explore the relative effectiveness of various control input devices and methods of controlling the LTM slave arms. A quick study will compare master/slave control using various combinations of the master arms' available seven degrees of freedom taken six at a time. That is, each of the master degrees of freedom will be locked one at a time and the same task performed with the remaining six. This study will be followed by a much larger study which will compare control of the LTM slave by a number of individual controllers including Kraft reduced-scale masters, CAE six-degree-of-freedom hand controllers, JPL force reflecting hand controllers, and Dimension Six hand controllers.

OBJECTIVES AND PHILOSOPHY OF DESIGN

The Laboratory Teleoperator Manipulator was designed to be used in a ground-based laboratory setting to study both robotic and telerobotic applications in space. Hence, its design includes characteristics considered necessary and desirable for use in space as well as design compromises to bridge the gap between human and purely robotic control. Previously, this type of research has centered around modified industrial manipulator arms such as the Unimate...
PUMA which are not designed for space operations or for general research in robotics. Man-in-the-loop control is currently required because the present level of robotic generality is insufficient for most near-term space applications. It is also likely that a hybridhuman/computer control will continue to be desirable as an option, however, even if human control is ultimately relegated to a backup or contingency for unanticipated situations. Control of the LTM requires a blending of fundamentally different design objectives to achieve simultaneously both good robotic and good teleoperator control. High joint back drivability for force reflection with minimum reflection of friction and inertia are the most important considerations for master/slave manual operation, but end effector accuracy and speed along with mechanical and control stiffness are the important considerations for robotic control [1].

Figures 1 and 2 show the LTM master and slave manipulator systems respectively. They each have two arms, each of which has seven DOF giving them kinematic redundancy. In master/slave operation, the most basic mode, the slave arms replicate the motion of the master arms according to any of several motion ratios as well as force reflection ratios. Force reflection is bilateral with the corresponding arm on the opposite arm pair. The links which make up the arms (i.e., upper arm, forearm, etc.) are modular and replace each other exactly except that the slave shoulder and upper arm are a scaled larger version to give the slave greater capability. Thus, the larger arm elements replace each other and the smaller elements replace each other. Movement of the links in the LTM arm is implemented by a differential jointly driven by a pinion gears which are individually driven by the computer. An analysis of variance will be applied to the data. Although we will find that the axis needing to be locked is a function of the subtask scenario, thus suggesting that the operator should be provided the capability to make this selection on a real-time basis.

CONTROL ELECTRONICS

The electrical and electronic hardware that implements the LTM control schemes and other related information processing consists of both commercially available systems and custom electronics [1]. Most of the custom electronics packages were designed to be housed in the arm links where sensory information could be locally assimilated, processed, and multiplexed for transmission to the more powerful external computing hardware. This permitted the use of serial communication lines thus reducing the cabling requirements sufficiently that all of the arm cables (power and communication) could be passed internally through the friction-drive differentials leaving none external. Each arm link contains basically two custom boards, a joint processor logic board and a joint processor power board, which are multilayered with high density surface-mounted components on both sides. The logic board monitors and processes sensor outputs, while the power board supplies power and reference voltages to components in the arm link. A transceiver on the power board communicates bidirectionally over a single optical fiber with a paired transceiver located at the external computers. The transceivers transmit and receive on different wavelengths communicating such parameters as motor positions and velocities; shaft pitch and yaw positions, velocities, and torques; and temperatures within the joint.

The bulk of the information processing electronics which controls the LTM consists of Motorola 68020 single-board computers operating in parallel over a VMEbus system. These are housed in two separate cabinets, one for the master and the other for the slave, and having intercabinet communication over a high-speed serial link. A Macintosh II computer connected to the master rack interfaces the human operator to the system through a variety of menu selections of optional control commands and input parameters. The sketch of Figure 7 shows the top-level organization of the electronics hardware. The master and slave racks also contain the pulse width modulator amplifiers which power the individual motors in the manipulators.

INITIAL STUDIES

Initial studies in the TSRL facility will evaluate teleoperator control of the LTM in terms of the relative advantages of various forms of operator input. Primarily these forms will consist of several specific input devices. However, one study will investigate optional ways of using subsets of the seven available degrees of freedom within the replica master. Subsets will each have six degrees of freedom. The concern is that when all seven degrees of freedom are active, the replica master will respond like a wet noodle to operator attempts at control inputs creating unintended coupling into axes that produce counterproductive motion of the slave. The full seven-degree-of-freedom master will be compared with several instances of the master with one degree of freedom locked. It is possible that we will find that the axis needing to be locked is a function of the subtask scenario, thus suggesting that the operator should be provided the capability to make this selection on a real-time basis.

Several experimental tasks will be used as a basis for the comparisons stated above. These studies in addition to providing data for the comparative evaluations will supply the first indications of the LTM general capabilities. Figure 8 shows hardware required for several different experiments laid out on both sides of the LTM track. The tasks to be performed will be both generic ones and ones which are subtasks selected from real space application scenarios. Each subject will perform each task with each of the various input devices to be compared. A balanced rotation of subjects and tasks will be devised to wash effects of learning and biased groupings of runs from the data. An analysis of variance will be applied to the data. Although the LTM master will be included as one of the input devices in this study, the "locked joint" comparisons using it will be made in a separate, but similarly conducted study.

Two task boards will be used. The first one, Figure 9, has been used previously by Langley, Grumman Aerospace, and SRI in earlier Teleoperator studies, thus providing us a link to and continuity
with previous work. This board measures generic alignment capabilities through peg-in-the-hole tasks and button-pushing which are performed with various sized pegs yielding hole-to-receptacle tolerances as small as .01". A second task board, Figure 10, looks at the rating of a number of different standard electrical connectors.

Three real application space tasks will be performed. Figure 11 is a picture of the hydrazine refueling probe proposed for an upcoming Shuttle experiment. The LTM slave will be controlled to release the probe from one receptacle and place it in another followed by turning a hex head bolt with a ratchet to secure the probe and then similarly turning five additional bolt heads to open individual valves in the probe.

The Access truss construction fixture (see fig. 8) is shown in the center on the far side of the track. Access was an experiment performed by astronauts in the Space Shuttle cargo bay [3]. Its objective was to demonstrate the construction of a simple truss in space and was accomplished by using a construction fixture on which to interconnect columns to nodes positioned at detents along slide rails. As truss bays were constructed, completed truss was slid off the end of the fixture. Figure 12 shows both the astronauts doing this and the Oak Ridge National Laboratory's M-2, dual-armed, force-reflecting manipulator system along with a human subject repeating the task in a ground-based, laboratory environment [4]. The LTM will be employed to perform the task in a manner similar to that used with the M-2.

The final task will be to use the hardware on the near side of the track to connect a long "Space Station type" column simultaneously to the receptacles on two Space Station nodes. This operation requires precise coordination of both slave arms. The truss in Figure 13 shows the latest Space Station Freedom concept. Although robotics probably will not be used to assemble this truss, it is important to look at and develop robotic capability for such applications to lay the groundwork for robotic assembly of the large repetitive trusses comprising the extremely large space platforms beyond Space Station Freedom. The actual Space Station Freedom columns are 5 meters long, but the ones we are using are only 3.94 meters long because of the working volume available in the lab. Figure 14 shows the same task being performed automatically in the Intelligent Systems Research Laboratory using two PUMA manipulators. This objective will be simply to release the column from the nodes, lift it well away from them, replace it within the nodes, and finally lock the columns in place.

Four subjects selected from a number of undergraduate engineering students on the basis of aptitude for manual control will perform the tasks. Each task/condition will be replicated five times and scored according to the time required to complete the task and the number of performance errors. Additional performance measures are being formulated to include total energy input to master, total energy output by slave, histograms of end effector rates, histograms of individual joint angle rates, histograms of end effector forces and torques, and histograms of individual joint torques. Assessments will be attempted to determine the best mix of attributes of control methodologies and input devices for particular jobs which have generic transfer. For instance, with one input device a given subject may perform the task in minimum time while with another he may do it with minimum energy, and with still another he may minimize performance errors. We may also find oddities such as a condition in which minimum energy for the operator is maximum energy for the slave.

The primary study variables will be subject, task, control input device, and mode of control input from controller to remote manipulator. Additional data for force reflection ratio will be acquired for those controllers which permit it as a variable.

Five different control input devices will be used:

1. Figure 15 shows the Kraft Controllers which are reduced scale masters having six degrees of freedom with force reflection in all but the wrist.
2. The JPL force reflecting hand controllers shown in Figure 16 have six degrees of freedom with force reflection in all axes.
3. Figure 17 shows the CAE hand controller. It has a full six degrees of freedom.
4. Figure 18 shows the Dimension Six controllers which have six degrees of freedom in force but no motion.

CONCLUDING REMARKS

The Laboratory Teleoperator Manipulator represents LaRC's newest, most advanced facility for evaluating the effects of subsystem changes on the overall performance of telerobotic systems. In this context, we have begun an extensive evaluation of hand controllers and other input devices. Results of the current effort should provide substantial aid to NASA programs, such as the Flight Telerobotic Servicer, which will apply telerobotics in actual space missions.

The true utility of results from individual telerobotic research projects and studies is realized only when they are incorporated into real or simulated systems and evaluated as the systems perform various tasks. Evaluations of this nature are needed by designers who synthesize full scale operational space telerobotic systems. Basic research in the LTM facility will contribute by integrating and testing at the system level enhancements resulting from very focused, individual, subsystem-level telerobotic research such as that produced by LaRC's Intelligent Systems Research Laboratory. Output of this effort will also help to relate telerobotic system performance in simple, well-controlled, generic tasks to performance in representative complex tasks. Likewise, it will relate results in representative, ground-based tasks to flight results. Finally, this work should promote the development of improved quantitative measures and indices of telerobotic performance as well as increase the data base of design requirements for future systems.

REFERENCES


Fig. 13 Space Station Freedom

Fig. 14 Truss Assembly Demonstration in the ISRL

Fig. 15 Kraft Controller

Fig. 16 JPL Force Reflecting Hand Controller

Fig. 17 CAE Hand Controller

Fig. 18 Dimension Six Controllers
Fig. 7 LTM Electronic Hardware

Fig. 8 Task Hardware for Input Evaluation Study

Fig. 9 Grumman/SRI Task Board

Fig. 10 Electrical Connector Task Board

Fig. 11 Hydrazine Refueling Probe

Fig. 12 Construction of the Access Truss